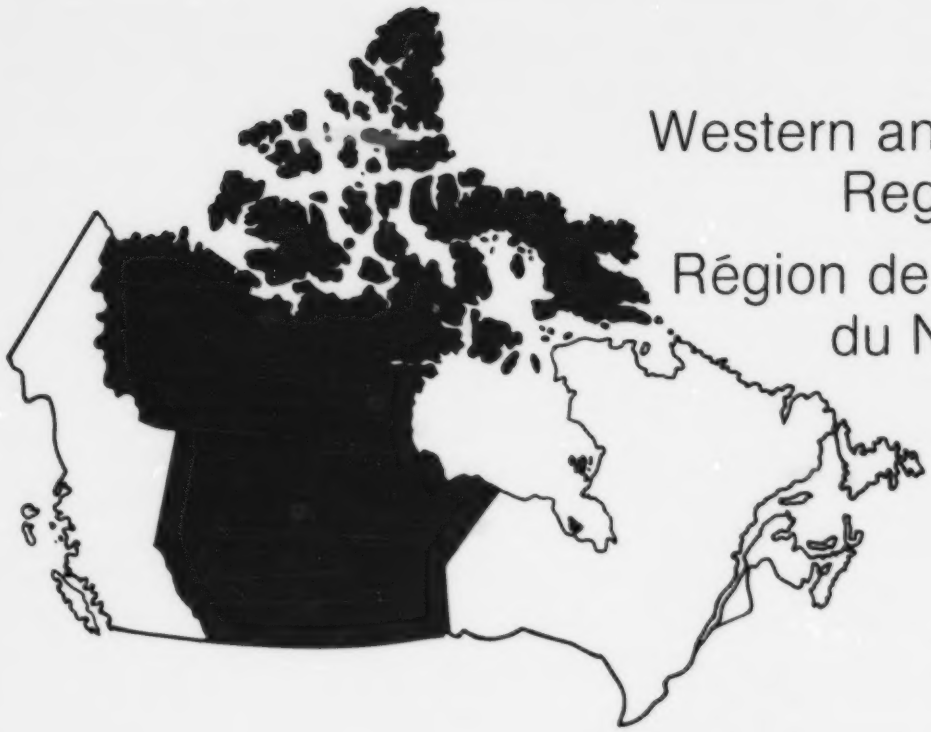
Environment Canada

Conservation and Protection

Environnement Canada

Conservation et Protection



Western and Northern Region

Région de l'Ouest et du Nord

Environmental Protection

Protection de l'environnement

Canada

RECLAMATION OF SULPHUR BLOCK BASEPADS

by

D. Parkinson and S. Leggett
Kananaskis Centre for Environmental Research
The University of Calgary
Calgary, Alberta

prepared for
Environmental Protection
Conservation and Protection
Western and Northern Region

March 1988

RECLAMATION OF SULPHUR
BLOCK BASEPADS

by D. Parkinson and S. Leggett
Kananaskis Centre for
Environmental Research
The University of Calgary
Calgary, Alberta

REPORT CP(EP)WNR87/88-12

ABSTRACT

Reclamation potential of contaminated soil from beneath a sulphur block basepad was evaluated in three 62-day greenhouse trials. The effect of lime ($CaCO_3$) and/or manure additions to pots of soil containing four different levels of total sulphur was tested through characteri- zation of soil and leachate chemistry and growth of reed canarygrass.

Unamended soils were acidic and contained high levels of soluble salts and available ammonium. Lime addition to sulphur-contaminated soils resulted in the maintenance of a neutral soil pH throughout the experiment and decreased extractable phosphorus levels. Manure amendation did not significantly increase soil pH. Leachates produced from pots containing acid soils were acidic, while those produced from neutralized soils were neutral.

No plant growth occurred in pots containing unamended, sulphur-contaminated soil. Lime applications were not effective in promoting plant growth at soil sulphur levels above 4%. This may be due to pore space reduction due to the physical presence of the lime. Soils amended with manure alone, did not produce any plant growth.

Soils contaminated with elemental sulphur should be treated with smaller initial lime applications over an extended time period than is currently practised. Prompt liming of soils contaminated with elemental sulphur is, however, recommended to minimize acidic leachate production.

TABLE OF CONTENTS

		Page
ABSTRACT		i
TABLE OF CONTENTS		ii
LIST OF TABLES		iii
1.	INTRODUCTION	1
	1.1 General Objective	1
	1.2 Specific Objectives	2
2.	MATERIALS AND METHODS	3
	2.1 Location of Study Site	3
	2.2 Greenhouse Trials	3
	2.2.1 Experimental Set-up	3
	2.2.2 Leachate Collection	5
	2.2.3 Soil Chemical Analyses	5
	2.2.4 Leachate Chemical Analyses	8
	2.3 Statistical Analysis of Data	8
3.	RESULTS	9
	3.1 Greenhouse Trials	9
	3.1.1 Total Sulphur in Soil Mixtures	9
	3.1.2 Aboveground Biomass	12
	3.1.3 Soil Chemical Characterization	12
	3.1.4 Leachate Chemical Characterization	24
4.	DISCUSSION	39
	4.1 Effect of Sulphur Contamination on Plant Growth and Soil Chemical Properties	39
	4.2 Effectiveness of Lime and Manure Amendments	41
	4.3 Chemical Characteristics of Leachates	46
5.	CONCLUSIONS	47
6.	LITERATURE CITED	48

LIST OF TABLES

Table		Page
3.1	Expected and observed total sulphur concentrations in the soil mixtures used for the growth trials . .	10
3.2	Differences in detection of known amounts of sulphur between limed and unlimed soils	11
3.3	Aboveground biomass (g dwt pot^{-1}) of reed canary-grass grown in soils containing four sulphur levels upon which reclamation treatments were superimposed.	13
3.4	The pH of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	14
3.5	Electrical conductivity values (mS cm^{1-}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	16
3.6	NO_3-N (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	17
3.7	NH_4-N (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	19
3.8	PO_4-P (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	20
3.9	SO_4-S (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	22
3.10	Texture classification of soils used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	23
3.11	Soil-buffer pH measurements, as determined by Shoemaker, McLean, and Pratt (SMP) method, of pot soil mixtures at experiment initiation	26

LIST OF TABLES (concluded)

Table		Page
3.12	Lime requirement recommendations (tonnes ha^{-1}) for pot soil mixtures as determined by SMP method. . . .	27
3.13	Actual amounts of lime applied to pot soils (tonnes ha^{-1}) to neutralize acidity produced by oxidation of elemental sulphur	28
3.14	The pH of leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed.	29
3.15	Electrical conductivity (mS cm^{1-}) of leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	31
3.16	NO_3-N (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	32
3.17	NH_4-N (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	33
3.18	PO_4-P (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	35
3.19	SO_4-S (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed	36
3.20	Soluble aluminum, iron, and manganese (mg L^{-1}) in leachates produced from selected pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed.	37

1.0 INTRODUCTION

Alberta produces 95% of Canada's elemental sulphur by converting the hydrogen sulphide (H_2S), present in sour natural gas, to elemental sulphur. The majority of sour gas plants in Alberta were built between 1950 and 1970. These plants stored the recovered elemental sulphur by pouring the molten form into a large block. The block was poured on top of a basepad which was also usually formed from molten sulphur. Many of the sulphur basepads were poured directly onto soil, with minimal pad preparation. This method of stockpiling was used by most operators as a means of storing the sulphur until a strong market for the element developed. There are presently in excess of 100 blocks in the province. The total area of basepads is estimated to be 100 hectares. These basepads range from a few hundred to 50,000 m^2 in area (Hyne 1986). Since 1980 few, if any, new basepads have been established in western Canada. Therefore, most blocks have been in place for at least ten years. The cleanup and reclamation of soil located below former sulphur blocks can be a difficult process if the basepad was poorly prepared. As much as 30% sulphur may remain in the soil once the initial cleanup phase is completed. Reclamation of these soils is required to prevent the generation of excess soil acidity.

1.1 GENERAL OBJECTIVE

To determine the level of sulphur that can be retained in the soil and still achieve reclamation of soil located below sulphur block basepads in Alberta.

1.2 SPECIFIC OBJECTIVES

1. To determine the effect of sulphur contamination on a number of soil chemical properties (plus nutrient leachability) and on plant growth; and

2. To determine the effectiveness of lime ($CaCO_3$) and lime plus manure applications to sulphur-contaminated soil in ameliorating soil conditions and encouraging plant growth.

2.0 MATERIALS AND METHODS

2.1. LOCATION OF STUDY SITE

Soil samples were taken near a sour gas plant located near Innisfail in south-central Alberta. Agriculture is the primary land use in the area. The soil is a Benalto Silt Loam belonging to the Black Chernozem order (Peters and Bowser 1960) and has developed on glacial till.

A sulphur block basepad was constructed at the gas plant site in 1960. Block preparations consisted of stripping the topsoil and removing surface biomass. A basepad composed of approximately 1 m of sulphur was poured directly onto the topsoil stripped surface. Sulphur was poured in the form of a block on top of the basepad. Between 1960 and 1985, sulphur inventory was both added and removed from the block, depending on market conditions. By 1985, the sulphur block had been removed and only the basepad remained. Sulphur-contaminated soil was removed from below a freshly exposed portion of basepad material.

Uncontaminated soil was taken from a farmer's field located ¼ km north of the gas plant. In order to obtain uncontaminated soil from approximately the same depth as contaminated soil, topsoil was stripped prior to sampling. Based on neutral soil pH values and total sulphur measurements of less than 0.5%, it was concluded that no significant soil acidification had occurred at the uncontaminated soil location. According to the area soil survey map (Peters and Bowser 1960), both locations are within the same soil unit.

Soil pits, 15 cm in depth, were dug below the basepad and in the farmer's field. Excavated soil, a mixture of A_e and B horizons, was transported back to the University where it was spread out on plastic sheets to air-dry. Once dried, the soil was put through a 4 mm sieve.

2.2. GREENHOUSE TRIALS

2.2.1 Experimental Set-Up

The greenhouse pot experiment consisted of three consecutive growth trials to determine the effects of four levels of sulphur on

aboveground biomass and selected soil chemical parameters. Two leaching trials were also run. The four levels of sulphur-contaminated soil were prepared by mixing the following proportions of uncontaminated soil with contaminated soil: (1) 100% uncontaminated soil; (2) 66.7% uncontaminated soil, 33.3% contaminated soil; (3) 33.3% uncontaminated soil, 66.7% contaminated soil, and (4) 100% contaminated soil. Soil mixture homogeneity was achieved by the use of a portable concrete mixer. Grab samples of the homogeneous soil were taken and analyzed for total sulphur and extractable NH_4-N, NO_3-N, and PO_4-P. Based on nutrient requirements from preliminary sampling, all pots were fertilized with 55 mg N kg^{-1} soil as an aqueous solution of ammonium nitrate. Results indicated that no phosphate additions were necessary.

Within each level of sulphur, four treatments were imposed: no treatment; addition of lime; addition of lime and manure; and addition of manure alone. Lime, in the form of agricultural grind $CaCO_3$, was added at a rate of three times the detected total sulphur. Manure was added as cattle manure at a rate of 40 tonnes ha^{-1}.

One replicate was comprised of sixteen pots (4 sulphur levels x 4 treatments). There were 5 replicates in each trial for a total of 80 pots. Open draining pots, 20 cm wide x 15 cm deep, were used with attached collection containers. Each trial was 62 days long. Pots were randomized on a weekly basis to eliminate position growth effects. Pot soil samples were taken at experiment initiation, between each trial, and at the end of the experiment. .

Pots were seeded with 50 seeds of reed canarygrass (Phalaris arundinacea) which corresponds to a seeding rate of 12.7 kg ha^{-1}. Once germination was completed, pots were individually watered to approximately 2/3 of their previously determined field capacity (~23%). At the end of each trial, aboveground biomass of each pot was clipped, dried for 48 h in an 80°C oven, and yield was recorded. Following each trial, soil from each pot was air dried, cultivated by thorough mixing, and soil samples (c.100 g) were taken for chemical analysis. The remaining soil was replaced in the pot.

2.2.2 Leachate Collection

At initiation and completion of the third growth trial, all pots were watered, by weight, to approximately field capacity (determined by pressure plate extraction method, McKeague 1978) plus 150 g. Following leachate drainage into collection containers, leachate was collected. Selected subsamples from the second trial were acidified with 0.1N HNO_3 for metal analyses. Leachate samples were filtered through Whatman GF/A filters. The pH and conductivity measurements were taken immediately following collection and filtration using a Fisher Accumet digital readout pH meter and an Industrial Instruments Inc. conductivity bridge meter, respectively. The nitrogen, phosphorus, and sulphur concentrations of the filtrates were determined using a Technicon II Auto Analyzer. Description of procedures are presented in Section 2.2.3. Samples were either analyzed within 48 hours of collection or frozen for analysis at a future date.

2.2.3 Soil Chemical Analyses

Soil samples for chemical analyses were air dried and passed through a 2 mm sieve. The following analytical procedures were used to characterize the soils. Unless noted in the descriptions below, all procedures were conducted as outlined by McKeague (1978).

A. pH

Forty mLs of water were added to 20 g of soil. The slurry was stirred initially and at 15 and 30 minutes. Samples then sat undisturbed for 30 minutes after which the pH of the soil:water mixture was determined using a Fisher Accumet digital readout pH meter.

B. Electrical conductivity

The soil:water suspension prepared for pH measurement was filtered through a Whatman GF/A filter. Electrical conductivity measurements of the filtrate were taken using an Industrial Instruments Inc. conductivity bridge meter.

C. Nitrogen analysis

Ten g of soil were extracted with 50 mℓ of 2 N KCl and shaken for 30 minutes. After filtration through a Whatman GF/A filter, the extract was analyzed colorimetrically on the Technicon II Auto Analyzer. Any extracts with a pH of less than 5 were raised to pH 5.0 by addition of sodium hydroxide. This neutralization was necessary to conform to operating requirements of the Technicon II Auto Analyzer.

Ammonium present in the soil extract was measured on the Technicon using the Berthelot Reaction (Technicon 1977). A green coloured compound occurs when a solution containing an ammonium salt is added to sodium phenoxide, followed by the addition of sodium hypochlorite. The concentration of this compound is measured by light absorbance.

In the automated determination of nitrate, extracted nitrate is reduced to nitrite by a copper-cadmium reductor column (Technicon 1978). The reduced ion then reacts with sulphanilamide. The resultant diazo compound then combines with N-1-naphthyethylenadiamine dihydrochloride to form a red colour, which is measured by light absorbance.

D. Phosphorous analysis

Ten g of soil were extracted with 50 mℓs of modified, medium strength Bray solution and shaken for 5 minutes. After filtration through a Whatman GF/A filter, the extract was analyzed colorimetrically on the Technicon using the reaction of ammonium molybdate in an acid medium to form molybdophosphoric acid (Technicon 1976). Reaction of this acid with ascorbic acid then forms a molybdenum blue complex which is measured by light absorbance.

E. Sulphate analysis

Ten g of soil were extracted with 0.1 M $CaCl_2$ and shaken for 30 minutes. After filtration through a Whatman GF/A filter, the extract was analyzed colorimetrically on the Technicon autoanalyzer.

The sulphate containing extract is reacted with barium chloride to form barium sulphate (Technicon 1978a). Uncomplexed barium reacts with methylthymol blue to form a blue coloured chelate. Uncomplexed methylthymol blue is gray. The amount of uncomplexed methylthymol blue is equal to the sulphate present.

F. Total sulphur analysis

Total sulphur concentrations were determined using a Leco SC132 system. Within this system, samples are combusted at approximately 1400°C in an oxygen atmosphere. Sulphur present in the sample is oxidized to SO_2 which is then measured by an infrared detector. A microprocessor formulates the analysis results which are then displayed on the control console.

The instrument was calibrated using sulphur-containing coal standards. To ensure that these standards were applicable for soil samples being analyzed, sulphur-containing soil standards were also prepared. Known quantities of soil containing non-detectable levels of total sulphur (i.e. < 0.1%) were combined with 99.996% pure sulphur prills so that total sulphur concentrations in the soil standards ranged from 0.05% to 16%. All soil samples and materials used for the soil standards were ground to pass through a 30 mesh sieve.

G. Lime requirement

Lime requirements of the initial soil samples were determined using the Shoemaker, McLean and Pratt (SMP) single-buffer method (Page et al. 1982). Ten g of soil was mixed with 10 mℓ of distilled water. Twenty mℓ of buffer solution was added to the soil suspensions. The mixture was shaken for 10 minutes and allowed to stand for 30 minutes after which the pH of the soil-buffer solution was read. The required level of agricultural ground limestone was determined from Page et al. (1982).

H. Particle size distributon

Estimates of sand, silt, and clay fractions in initial soil samples were determined using a soil hydrometer (Black 1965). The determination of the fractions is based on Stoke's law which states that the velocity of a particle settling in a liquid is directly proportional to its size and density (Brower and Zar 1977). Once the soil sample percentage of each fraction is known, soil texture can be determined using a textural class triangle (Hausenbuiller 1978).

One hundred mℓ of Calgon solution and 300 mℓ of distilled water were added to 40 g of soil and allowed to soak overnight. The suspension was then homogenized in an electric mixer, transferred to a cylinder, and brought to 1 ℓ volume. The suspension in the cylinder was thoroughly mixed with a plunger. Hydrometer readings were taken at a series of time intervals ranging from 30 sec to 18 h. The percentage of each fraction was calculated according to the equations in McKeague (1978).

2.2.4 Leachate Chemical Analyses

Leachate chemical analyses were determined using the relevant instruments used for soil analyses as described in Section 2.2.3. In addition, 15 subsamples of the second leachate collection (20 mℓ) were acidified with 0.1 mℓ of concentrated HNO_3. These samples were then analyzed for Al, Fe, and Mn using an inductively coupled plasma spectrophotometer.

2.3 STATISTICAL ANALYSIS OF DATA

All data were tested for significance with a two-way analysis of variance (ANOVA) and Scheffe multiple range test. Homogeneity of variances for all data sets was tested using the F_{max}-test. Log transformations of data sets were performed when necessary. Notation of transformed data is made where appropriate.

There was a significant interaction between the two factors (reclamation trials and sulphur levels) in all analyses of variance. Values for each measured parameter were, therefore, tested individually against all other values for the same parameter in the Scheffe multiple range test. The accepted level of significance for all tests was $p<0.05$.

3.0 RESULTS

3.1. GREENHOUSE TRIALS

Data collected from the greenhouse trials will be presented in Section 3.1. Separate subsections will deal with: (1) verification of the soil sulphur present, (2) aboveground biomass yields from growth trials, (3) soil chemical characterization, and (4) leachate chemical characterization. Because lime was added to the soil in proportion to sulphur concentration, no lime was added to control soils. The only amendment added to control soils, therefore, was manure.

3.1.1. Total Sulphur in Soil Mixtures

Expected total sulphur concentrations of soils were verified using samples taken from all pot mixtures. The total sulphur concentration of unlimed soil correlated closely with expected values based on the ratios of clean:contaminated soil (Table 3.1). Reduced sulphur levels were detected in limed soils, especially at high levels of lime. The hypothesis that this was an instrument detection problem and not a true difference between soils within each level was tested by preparing 2 sets of standards. The first set contained known amounts of sulphur and soil while the second set contained known amounts of sulphur, soil, and lime. Results from this investigation confirmed that the presence of lime inhibited sulphur detection by the Leco SC 132 (Table 3.2). Given this observation and the fact that soil within each sulphur level for the four reclamation treatments was taken from the same homogenized, bulked sample, it is unlikely that significant differences existed between total sulphur values within each level. Small differences that may have been present, due to varying particle sizes of elemental sulphur and any variation within bulked samples, are probably insignificant compared to differences in total sulphur amongst the four sulphur levels.

TABLE 3.1. Expected* and observed total sulphur concentrations in the soil mixtures used for the growth trials. Data are means (n=25) ± standard deviations.

Clean: Contaminated Soil Ratio	Expected Total Sulphur Values (%)	Reclamation Treatments (observed total sulphur values (%))			
		No Treatment	Lime	Lime and Manure	Manure
3:0	0.0	<0.1	<0.1	<0.1	<0.1
2:1	4.0	4.7±0.5	4.2±0.7	3.7±0.5	4.8±0.4
1:2	8.0	9.8±1.0	7.7±0.5	7.4±0.9	9.6±0.9
0:3	12.0	14.9±0.8	10.8±0.9	10.7±0.8	14.2±1.1

*based on clean:contaminated soil ratios

TABLE 3.2. Differences in detection of known amounts of sulphur between limed and unlimed soils. Data are means (n=10) ± standard deviations.

Expected S Values (%)	Observed Sulphur Values (%)	
	Soil and Sulphur	Soil, Sulphur, and Lime
4.0	3.6±0.3	3.5±0.5
6.9	7.1±0.7	6.5±1.3[1]
8.0	7.6±1.4[2]	7.6±0.6
12.0	12.8±0.7	10.3±0.9
16.0	15.3±0.7	13.6±1.3

[1] n = 5
[2] n = 9

3.1.2 Aboveground biomass

Although absolute amounts of biomass varied with trial number, general growth response trends were similar for all three trials (Table 3.3). No growth occurred in either untreated or manure-treated soils that contained detectable amounts of sulphur. Good growth was recorded in all control pots.

Reed canarygrass only grew in sulphur-contaminated soil when lime was applied. The presence of lime in contaminated soil did not, however, ensure successful plant establishment. In all three trials, biomass for the soil containing 14% sulphur was not significantly different from zero for the calculated Scheffe 95% confidence interval. In the last 2 trials, aboveground biomass in the 9% sulphur treatments was significantly lower than that in control soils. In trial 3, grass growth in the limed 4% sulphur soil was less than 50% of that in the control soil. There was, approximately, a 75% yield reduction in the limed, 9% sulphur soil compared to yields from control soil. Addition of manure to limed, sulphur-contaminated soils did not significantly improve yields.

Treatments with zero values and biomass values for 14% sulphur soils were not included in the ANOVA, as inclusion of these data invalidated the assumptions of an ANOVA (Zar 1984).

3.1.3 Soil Chemical Characterization

A. pH measurements

Prior to the growth trials, the pH of all soils was neutral (i.e., pH 6.0-7.5), except the values for unlimed sulphur-contaminated soils (Table 3.4). The pH of these acid soils significantly decreased with increasing soil sulphur concentration. At the conclusion of the first trial, the pH of the 9% and 14% sulphur-containing soils were no longer significantly different. Throughout the experiment, there were no pH differences amongst any of the limed, sulphur-contaminated soils. Manure additions to limed and unlimed soils did not alter soil pH values.

TABLE 3.3. Aboveground biomass (g dwt pot^{-1}) of reed canarygrass grown in soils containing four sulphur levels upon which reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime + Manure	Manure
a) Trial 1				
<0.1	2.32±1.08	1.62±0.62^{a}	3.06±0.65^{b}	3.17±0.83
4	0.00	2.80±0.80^{b}	1.97±0.87^{ab}	0.00
9	0.00	0.55±0.51^{a}	1.06±1.11^{ab}	0.00
14	0.00	0.00	0.05±0.11	0.00
b) Trial 2				
<0.1	5.61±1.39	5.59±0.64^{bc}	6.90±1.07^{c}	7.18±0.65
4	0.00	2.41±0.98^{ab}	3.64±1.37^{b}	0.00
9	0.00	0.43±0.21^{a}	0.75±0.56^{a}	0.00
14	0.00	0.03±0.02	0.03±0.03	0.00
c) Trial 3				
<0.1	7.15±1.09	6.78±0.91^{b}	6.71±1.44^{b}	5.76±0.96
4	0.00	2.00±0.73^{a}	2.60±0.54^{a}	0.00
9	0.00	0.79±0.35^{a}	0.80±0.65^{a}	0.00
14	0.00	0.03±0.07	0.30±0.26	0.00

[1] Two-way ANOVA was applied only to data from the 2 lime treatments and the first 3 soil sulphur levels. MSE for each trial was (1) 0.6178, (2) 0.7929, and (3) 0.7171 respectively. Significant differences amongst means were detected by the Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p<0.05$).

TABLE 3.4. The pH of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1].

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
a) Prior to 1st growth trial				
<0.1	6.3±0.1^{d}	6.4±0.1^{d}	6.4±0.1^{d}	6.4±0.1^{d}
4	4.4±0.1^{c}	7.2±0.1^{e}	7.3±0.1^{e}	4.5±0.1^{c}
9	3.2±0.1^{b}	7.2±0.1^{e}	7.2±0.1^{e}	3.4±0.1^{b}
14	2.3±0.1^{a}	7.2±0.1^{e}	7.2±0.1^{e}	2.4±0.1^{a}
b) Following 1st growth trial				
<0.1	6.0±0.1^{c}	5.9±0.1^{c}	6.2±0.1^{c}	6.2±0.1^{c}
4	2.3±0.2^{b}	7.0±0.1^{d}	7.1±0.1^{d}	2.4±0.2^{b}
9	1.9±0.2^{a}	7.1±0.1^{d}	7.1±0.1^{d}	1.8±0.1^{a}
14	1.6±0.1^{a}	7.1±0.1^{d}	7.1±0.1^{d}	1.6±0.1^{a}
c) Following 2nd growth trial				
<0.1	5.8±0.3^{c}	5.9±0.1^{cd}	6.3±0.3^{d}	6.3±0.1^{d}
4	2.1±0.1^{b}	7.1±0.1^{e}	7.1±0.1^{e}	2.1±0.1^{b}
9	1.6±0.1^{a}	7.2±0.1^{e}	7.2±0.1^{e}	1.6±0.1^{a}
14	1.5±0.1^{a}	7.2±0.1^{e}	7.3±0.1^{e}	1.5±0.1^{a}
d) Following 3rd growth trial				
<0.1	5.9±0.2^{c}	6.0±0.1^{cd}	6.3±0.2^{d}	6.3±0.1^{d}
4	1.9±0.1^{b}	7.1±0.1^{e}	7.1±0.1^{e}	2.0±0.1^{b}
9	1.7±0.1^{a}	7.1±0.1^{e}	7.1±0.1^{e}	1.6±0.1^{ab}
14	1.4±0.1^{a}	7.1±0.1^{e}	7.1±0.1^{e}	1.4±0.2^{a}

[1] Data in each trial were analyzed by two-way ANOVA. MSE for each trial was (1) 0.00322, (2) 0.01217, (3) 0.01495, and (4) 0.01219. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p<0.05$).

Throughout the three growth trials, the pH of limed soils remained neutral, while the pH of unlimed sulphur-contaminated soils decreased. The greatest pH decrease in these soils occurred during the first growth trial. The pH of untreated control soils decreased slightly over time, while the pH of manure-treated control soil remained stable.

B. Conductivity values

Control soils had the lowest conductivity (E.C.) values of all soils throughout the experiment (Table 3.5). The conductivity of limed soils for the three growth trials was within an acceptable range (E.C. $\leq$ 4.0 mS cm^{-1}) for supporting plant growth (Hausenbuiller 1978). Unlimed soils from the 14% sulphur level were the only soils with E.C. values greater than 4.0 mS cm^{-1} in the first sampling.

While there was little change in the E.C. of limed soils over time, the E.C. of untreated and manure-treated, sulphur-contaminated soils increased between experiment initiation and completion of the first growth trial. No similar increases in E.C. occurred again. From the end of the first growth trial to experiment termination, the E.C. of all unlimed, contaminated soils was greater than 4 mS cm^{-1}.

In all trials, the conductivity of limed soils was significantly lower than that of unlimed, contaminated soils. Following the first growth trial, no significant differences existed between limed, contaminated soils. The application of manure to soils did not significantly affect conductivity values.

C. Nitrogen availability in soils

Nitrogen, determined as KCl-extractable nitrate-nitrogen and ammonium-nitrogen, was measured in soils used in the greenhouse experiment. Nitrate values of samples taken prior to experiment initiation had less variation among the 5 replicates than did samples from the last three sampling periods (Table 3.6). In the first sampling period, limed soils had significantly higher nitrate values than unlimed soils. This general trend continued in the second

TABLE 3.5. Electrical conductivity values (mS cm^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
a) Prior to 1st growth trial				
<0.1	0.36±0.02^{a}	0.38±0.02^{a}	0.55±0.02^{b}	0.56±0.03^{b}
4	1.89±0.06^{c}	1.84±0.11^{c}	2.04±0.11^{c}	2.03±0.06^{c}
9	2.73±0.09^{e}	2.29±0.04^{d}	2.45±0.03^{de}	2.93±0.06^{e}
14	4.82±0.27^{f}	2.32±0.03^{d}	2.51±0.04^{de}	4.47±0.19^{f}
b) Following 1st growth trial				
<0.1	0.58±0.12^{a}	0.66±0.17^{a}	0.70±0.15^{a}	0.60±0.15^{a}
4	10.0 ±2.2^{cd}	2.40±0.07^{b}	2.54±0.07^{b}	9.1 ±1.8^{c}
9	15.3 ±2.5^{d}	2.37±0.10^{b}	2.50±0.08^{b}	18.3 ±3.7^{d}
14	21.2 ±3.2^{d}	2.32±0.11^{b}	2.44±0.07^{b}	21.2 ±5.3^{d}
c) Following 2nd growth trial				
<0.1	0.87±0.28^{a}	0.65±0.10^{a}	0.71±0.38^{a}	0.64±0.14^{a}
4	14.1 ±1.8^{c}	2.44±0.07^{b}	2.59±0.11^{b}	13.5 ±1.4^{c}
9	21.8 ±3.5^{d}	2.36±0.07^{b}	2.47±0.08^{b}	23.4 ±2.6^{d}
14	24.3 ±3.8^{d}	2.29±0.07^{b}	2.47±0.08^{b}	23.1 ±5.1^{d}
d) Following 3rd growth trial				
<0.1	0.64±0.29^{a}	0.49±0.09^{a}	0.45±0.28^{a}	0.48±0.11^{a}
4	15.7 ±2.7^{c}	2.72±0.35^{b}	2.54±0.11^{b}	15.6 ±1.6^{c}
9	18.0 ±2.0^{c}	2.50±0.08^{b}	2.55±0.08^{b}	19.8 ±1.6^{c}
14	21.5 ±5.0^{c}	2.39±0.08^{b}	2.61±0.09^{b}	23.3 ±7.3^{c}

[1] Data in each trial were analyzed by two-way ANOVA following log transformation. MSE for each trial was (1) 0.00010 (2) 0.00302, (3) 0.00250, and (4) 0.00320. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p<0.05$).

TABLE 3.6. NO_3-N (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
a) Prior to 1st growth trial				
<0.1	44.1±1.1^{cd}	44.1±1.9^{cd}	64.6±1.0^{de}	64.6±7.6^{de}
4	29.7±1.8^{b}	70.8±2.1^{e}	113.4±2.1^{f}	47.6±1.3^{cd}
9	25.4±3.0^{ab}	56.4±3.0^{de}	90.3±7.4^{ef}	39.8±0.9^{c}
14	20.4±3.6^{a}	52.3±2.7^{d}	90.4±2.7^{ef}	35.3±3.6^{bc}
b) Following 1st growth trial				
<0.1	64.7±28.8^{b}	76.0±16.8^{b}	65.9±19.2^{b}	62.9±21.4^{b}
4	15.9±4.3^{ab}	35.9±37.4^{b}	93.3±59.1^{b}	31.5±9.8^{b}
9	2.9±2.7^{ab}	37.9±34.7^{b}	36.3±25.2^{b}	4.1±2.2^{ab}
14	1.4±0.2^{a}	4.9±5.1^{ab}	14.4±20.4^{ab}	4.4±7.2^{ab}
c) Following 2nd growth trial				
<0.1	24.6±24.4^{a}	51.1±20.2^{b}	13.5±14.4^{ab}	10.1±12.0^{ab}
4	42.0±7.5^{b}	3.9±1.1^{a}	5.8±4.2^{ab}	48.1±5.9^{b}
9	2.9±1.0^{a}	3.3±0.7^{a}	3.2±0.8^{a}	10.1±8.6^{ab}
14	2.8±0.9^{a}	1.8±1.2^{a}	1.8±1.4^{a}	4.4±1.9^{a}
d) Following 3rd growth trial				
<0.1	2.1±0.4^{a}	3.8±4.5^{a}	2.3±0.4^{a}	2.2±0.5^{a}
4	23.6±18.0^{b}	3.8±0.8^{a}	2.7±0.4^{a}	48.8±22.5^{b}
9	3.6±0.5^{a}	2.6±0.7^{a}	2.1±0.7^{a}	10.7±15.8^{ab}
14	2.2±0.3^{a}	1.6±0.3^{a}	1.3±0.2^{a}	2.9±0.5^{a}

[1] Data in each trial were analyzed by two-way ANOVA following log transformation. MSE for each trial was (1) 0.00096 (2) 0.12235, (3) 0.07120, and (4) 0.04098. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < 0.05$).

sampling period, although, due to high variance within replicate determinations, the differences were not significant.

Nitrate values for the 4% unlimed, sulphur soils in the final two sampling periods significantly increased compared with limed soils. Nitrate levels in all other soils were not significantly different from those in control soils.

Nitrate values of the unlimed, 9% and 14% sulphur soils dropped between the first and second sampling periods. Limed soil values, however, did not drop until the third sampling period. Manure addition to soils did not affect nitrate values. Nitrate values in the uncontaminated soils decreased between the third and fourth sampling period. Between these two sampling periods, two pot leaching trials were carried out.

Values for ammonium-nitrogen varied much less among trials than did nitrate-nitrogen values (Table 3.7). Trends in ammonium levels were similar for all four sampling periods. Ammonium levels in control soils dropped gradually over time, unlike nitrate levels. Ammonium concentrations in limed soil did not differ significantly from control samples. In contrast, all unlimed soils containing sulphur had significantly higher ammonium levels than those in the control soils. The addition of manure did not affect soil ammonium levels.

D. Phosphorus values

Observed trends in phosphate-phosphorus levels were similar for all sampling periods (Table 3.8). Phosphorous concentrations in untreated and manure-treated soils remained constant as soil sulphur concentration increased, with one exception. Samples of the 4% sulphur soil taken following the first and second growth trials had lower phosphorus concentrations than those at higher sulphur levels.

Manure addition increased phosphorus concentration in all soils. Lime addition to sulphur soils significantly decreased phosphorus levels. Manure addition to limed soils raised phosphorus values, but they still remained low compared with control soils. Lowest phosphorus values occurred in the highest sulphur-contaminated, limed soil.

TABLE 3.7 NH_4-N (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 1st growth trial				
<0.1	22.1±4.5^{ab}	20.7±1.5^{ab}	18.8±3.3^{a}	18.4±4.0^{a}
4	44.0±2.0^{c}	29.3±1.2^{b}	25.3±2.3^{a}	37.9±1.1^{bc}
9	59.3±12.0^{cd}	39.6±4.5^{bc}	35.2±3.6^{bc}	58.3±2.3^{cd}
14	78.5±3.8^{d}	52.6±3.0^{c}	50.7±2.2^{c}	79.8±2.6^{d}
b) Following 1st growth trial				
<0.1	12.7±2.8^{a}	16.8±4.0^{a}	8.6±1.7^{a}	10.3±3.5^{a}
4	97.0±23.1^{b}	9.4±2.4^{a}	11.0±2.0^{a}	125 ±17^{b}
9	109.±13^{b}	13.1±2.9^{a}	11.3±3.3^{a}	134 ±17^{b}
14	146 ±12^{b}	11.0±7.0^{a}	8.8±4.0^{a}	178 ±37^{b}
c) Following 2nd growth trial				
<0.1	6.9±0.9^{a}	7.0±1.2^{a}	6.1±0.8^{a}	6.5±1.3^{a}
4	139 ±14^{b}	5.7±0.9^{a}	5.5±0.7^{a}	165 ±16^{b}
9	158 ±23^{b}	5.7±0.5^{a}	6.2±1.9^{a}	216 ±38^{b}
14	193 ±61^{b}	4.5±0.5^{a}	4.5±0.6^{a}	197 ±83^{b}
d) Following 3rd growth trial				
<0.1	4.4±0.4^{a}	4.5±0.6^{a}	4.6±0.9^{a}	4.3±0.1^{a}
4	191 ±53^{b}	4.6±0.4^{a}	4.8±0.5^{a}	243 ±14^{b}
9	264 ±27^{b}	3.6±0.4^{a}	3.5±0.2^{a}	290 ±8^{b}
14	223 ±16^{b}	4.7±0.6^{a}	3.3±0.5^{a}	193 ±51^{b}

[1] Data in each trial were analyzed by two-way ANOVA following log transformation. MSE for each trial was (1) 0.00242, (2) 0.01706, (3) 0.00967, (4) 0.00305. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < 0.05$).

TABLE 3.8. PO_4-P (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=3) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 1st growth trial				
<0.1	21.3±0.7^{d}	24.4±3.8^{d}	46.7±5.9^{def}	47.8±5.3^{ef}
4	23.9±1.5^{d}	9.3±0.4^{c}	13.8±2.3^{cd}	48.5±1.7^{cf}
9	26.1±1.8^{de}	4.4±0.7^{b}	9.1±0.9^{bc}	61.6±1.0^{ef}
14	21.3±1.0^{d}	1.3±0.4^{a}	4.4±0.7^{b}	55.2±1.8^{ef}
b) Following 1st growth trial				
<0.1	21.2±1.4^{bcd}	21.2 ±0.9^{bcd}	40.0±1.0^{cd}	37.1±1.3^{cd}
4	6.2±2.6^{ab}	7.6±0.8^{ab}	14.2±3.2^{b}	9.8±3.2^{b}
9	17.8±5.0^{bc}	5.1±0.3^{ab}	10.4±1.1^{b}	41.3±7.6^{cd}
14	18.9±3.5^{bc}	2.9±1.1^{a}	6.0±0.8^{ab}	49.2±13.1^{cd}
c) Following 2nd growth trial				
<0.1	22.7±1.4^{bc}	22.2±1.5^{bc}	41.2±2.8^{bc}	39.7±1.8^{bc}
4	8.0±4.9^{ab}	7.2±1.8^{ab}	15.0±4.0^{bc}	10.8±7.1^{ab}
9	34.4±4.9^{bc}	5.9±1.1^{ab}	11.4±0.4^{ab}	59.7±8.4^{bc}
14	26.2±4.7^{bc}	2.2±1.0^{a}	4.1±0.8^{ab}	56.0±8.7^{bc}
d) Following 3rd growth trial				
<0.1	18.4±1.6^{bc}	17.5±0.4^{bc}	38.7±2.3^{cd}	36.1±1.6^{cd}
4	17.4±11.6^{bc}	11.5±0.2^{bc}	24.3±2.1^{bcd}	26.2±4.8^{cd}
9	28.3±6.0^{cd}	9.2±2.8^{b}	16.5±5.6^{bc}	51.1±3.4^{cd}
14	24.4±4.7^{bcd}	0.23±0.06^{a}	0.53±0.11^{a}	48.8±6.9^{cd}

[1] Data in each trial were analyzed by two-way ANOVA following log transformation. MSE for each trial was (1) 0.00371, (2) 0.00666, (3) 0.01945, and (4) 0.00808. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < .05$).

E. Sulphate values

Sulphate levels measured in sulphur-contaminated soils were significantly higher in all trials compared with those soils that did not contain sulphur (Table 3.9). Sulphate values in control soils remained constant throughout the growth trials. Sulphate concentrations in sulphur-contaminated soils increased with increasing soil sulphur concentrations. All soils within each sulphur treatment contained approximately the same amount of sulphate prior to the first growth trial. From the end of the first growth trial to experiment termination, however, sulphate levels were significantly higher in the unlimed, sulphur-contaminated soils compared to the limed, sulphur-contaminated soils. Throughout the experiment, sulphate production was highest in the unlimed, sulphur-contaminated soils. The low sulphate values in the limed soils, compared to the values measured in the unlimed sulphur-contaminated soils could be the result of gypsum formation; thereby reducing the amount of sulphate available for extraction by $CaCl_2$. The presence of manure did not influence soil sulphate concentrations. Although the sulphate data did not pass the F_{max}-test, it was assumed that the ANOVA was robust enough to withstand the heterogeneity of variances inherent in this data set.

F. Soil texture

Texture measurements were determined for soil from each combination of sulphur level and reclamation treatment. The majority of soils were classified in the silt loam textural class (Table 3.10). This is in agreement with field observations that the top 30 cm of soil is silt loam in texture (Peters and Bowser 1960).

According to Brady (1984), all determined textures fall into the medium texture class with the exception of clay loam and sandy loam soils. The control soil determined as a clay loam had a moderately fine texture, while the soil containing 14% sulphur amended with lime and manure had a moderately coarse texture.

In general, no major texture differences were measured despite the varying levels of sulphur, lime, and manure present in the soils.

TABLE 3.9 SO_4-S (mg kg^{-1}) of pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=3) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 1st growth trial				
<0.1	26±25[a]	22±25[2,a]	33±10[a]	61±10[2,a]
4	2840±11[b]	2400±70[b]	2450±80[b]	2770±90[b]
9	5220±100[d]	4310±50[c]	4330±10[c]	5210±200[e]
14	7860±200[e]	5610±110[d]	5530±140[d]	7440±170[e]
b) Following 1st growth trial				
<0.1	150±50[a]	200±30[2,ab]	490±200[b]	140±30[2,a]
4	27,450±7840[d]	7910±60[c]	7930±70[c]	23,160±5620[d]
9	39,080±6010[d]	7910±110[c]	8150±40[c]	41,750±7560[d]
14	33,320±2450[d]	7600±70[c]	7700±110[c]	32,550±10,540[d]
c) Following 2nd growth trial				
<0.1	990±440[a]	540±240[2,a]	620±590[a]	450±190[2,a]
4	38,480±7340[c]	7930±230[b]	8240±110[b]	34,670±2380[c]
9	50,450±5440[c]	8130±140[b]	8220±220[b]	55,150±3240[c]
14	35,280±5220[c]	7680±50[b]	7550±450[b]	38,940±1810[2,a]
d) Following 3rd growth trial				
<0.1	880± 370[a]	470±260[2,a]	520±620[a]	310±250[2,a]
4	39,480±7010[bc]	8000±150[a]	8280±70[a]	42,440±1250[c]
9	42,740±3060[b]	8040±90[a]	8020±70[a]	45,560±1390[c]
14	28,470±6770[b]	7720±50[a]	7950±160[a]	32,550±880[bc]

[1] Data in each trial were analyzed by two-way ANOVA. Data from the initial and final trials were not transformed prior to analysis, although other data were log transformed. MSE for each trial was (1) 11356.9, (2) 0.00874, (3) 0.01849, and (4) 7297339. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p<.05$).

[2] n = 2

TABLE 3.10. Texture classification of soils used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed.

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
<0.1	Clay loam	Silt loam	Silt loam	ND
4	Silt loam	Silt loam	Loam	Silt loam
9	Silt loam	Loam	Loam	Silt loam
14	Loam	Loam	Sandy Loam	Silt loam

ND = not determined.

G. Lime requirement

The lime requirement of the soil mixtures was determined to compare actual amounts of lime added with that required to neutralize existing soil acidity. Soil-buffer pH measurements of the mixtures are presented in Table 3.11. Limed soils had the highest soil-buffer pH while unlimed, sulphur-contaminated soils had the lowest pH values. Lime requirement recommendations to neutralize the top 15 cm of soil to pH 7.0, as determined by Page et al. (1982), are presented in Table 3.12. Minimal amounts of lime were required to raise control soil pH to 7.0. No additional lime was required in the previously limed, sulphur-contaminated soil. The amount of lime required to neutralize unlimed, sulphur-contaminated soils increased with increasing soil sulphur level. The soil-buffer pH values for the unlimed 14% sulphur soil were below the lowest soil-buffer pH of 4.8 recorded in Page et al. (1982). Lime requirement values for soil-buffer pH's measured at the 14% soil sulphur level were estimated based on the assumption that for every 0.1 drop in pH unit, 1.05 times the amount of lime was required. This assumption was validated for lime requirement values within pH range of 5.0-4.8 in Page et al. (1982).

The amount of lime actually applied to the pots is presented in Table 3.13. Lime values from Tables 3.12 and 3.13 can be directly compared for the various soil sulphur levels. The actual amount of lime applied to pots exceeded that required to neutralize existing soil acidity by at least ten-fold for all soil sulphur levels.

For both the 9% and 14% sulphur levels, the soil-buffer pH values were higher for manure-treated soil than for untreated soil. This resulted in a corresponding decrease in lime requirement for the manure-treated soils at these two sulphur levels.

3.1.4 LEACHATE CHEMICAL CHARACTERIZATION

Data for leachates produced both prior to and following the third growth trial are presented in the following six subsections. Addition of manure to soils did not produce statistical differences in parameters measured in the produced leachates. In the second leaching

episode, data from limed, 14% sulphur soil were excluded from statistical analyses as only one replicate remained in the experiment.

TABLE 3.11. Soil-buffer pH measurements, as determined by Shoemaker, McLean and Pratt (SMP) method, of pot soil mixtures at experiment initiation. Data are means (n=3) ± standard deviations.

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
<0.1	6.67 ± 0.04	6.76 ± 0.03	6.80	6.82 ± 0.07[1]
4	5.95 ± 0.04	7.24 ± 0.03	7.22 ± 0.02	6.08 ± 0.02
9	5.32 ± 0.05	7.27 ± 0.02	7.27 ± 0.02	5.60 ± 0.22
14	4.18 ± 0.08	7.30 ± 0.03	7.30 ± 0.01	4.37 ± 0.05

[1] n = 2

TABLE 3.12. Lime requirement recommendations (tonnes ha^{-1}) for pot soil mixtures as determined by SMP method. Recommendations are based on amount of agricultural grind limestone required to obtain a pH of 7.0 in top 15 cm of soil.

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
<0.1	4.0	2.4	2.4	2.4
4	16.1	not required	not required	16.1
9	28.4	not required	not required	23.0
14	66 (est.)[1]	not required	not required	60 (est.)

[1]Estimated values extrapolated from Table 12.1 (Page et al. 1982).

TABLE 3.13. Actual amounts of lime applied to pot soils (tonnes ha^{-1}) to neutralize acidity produced by oxidation of elemental sulphur.

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
<0.1	NA	NA	NA	NA
4	NA	288	276	NA
9	NA	555	534	NA
14	NA	893	857	NA

NA = not applicable

TABLE 3.14. The pH of leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments			
	No Treatment	Lime	Lime and Manure	Manure
a) Prior to 3rd growth trial				
<0.1	5.3±1.0^{bc}	4.6±1.2^{b}	5.1±0.9bc	5.8±1.0^{bc}
4	1.7±0.2^{a}	7.2±0.3^{c}	6.8±0.7^{c}	1.8±0.1^{a}
9	0.9±0.2^{a}	7.0±0.2^{c}	6.9±0.3^{c}	0.9±0.1^{a}
14	0.5±0.1^{a}	6.9±0.2^{c}	7.1±0.1^{c}	0.5±0.1^{a}
b) Following 3rd growth trial				
<0.1	4.9±0.7^{b}	5.0±0.2^{b}	5.5±0.5^{b}	5.3±0.3^{b}
4	1.3±0.4^{a}	7.1±0.4^{c}	7.3±0.1^{c}	1.4±0.2^{a}
9	1.0±0.1^{a}	7.3±0.2^{c}	7.4±0.1^{c}	1.0±0.1^{a}
14	0.7±0.1^{a}	7.5[2]	7.5±0.1^{c}	0.7±0.2^{a}

[1]Data in both trials were analyzed by two-way ANOVA. MSE for each trial was (1) 0.31922, and (2) 0.07568. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < 0.05$).

[2] n = 1

A. pH of leachates

Similar trends in pH values were produced from both leaching episodes (Table 3.14). Three distinct groups of pH measurements were separated statistically. Leachates produced from unlimed, sulphur-contaminated soils were strongly acidic. The pH of leachates generated from control soils were mildly acidic, while the pH of leachates produced from limed, sulphur-contaminated soils were neutral. There were no significant differences in leachate pH within any of these three groups.

B. Leachate conductivity

Similar trends in conductivity values existed for both leaching episodes (Table 3.15). Conductivity values were highest in leachates produced from unlimed, sulphur-contaminated soil. Within this group, conductivity values increased with increasing total sulphur concentration. Leachates from limed, sulphur-contaminated soil were at least ten-fold lower than those from their unlimed counterparts. There were no significant differences in conductivity values amongst leachates produced from limed, sulphur-containing soils. Leachate from control soils had the lowest conductivity values of the experiment. No major changes in the magnitude of conductivity values occurred over time.

C. Soluble nitrogen concentrations in leachates

Similar trends in nitrate and ammonium values occurred in both leaching episodes (Tables 3.16 and 3.17). Leachates produced from control soils and from limed, sulphur-contaminated soils were not significantly different. In the first leaching trial, more nitrate-nitrogen was produced from these soils than ammonium. Leachates produced in the second trial from the control and limed, sulphur-contaminated soils contained similar concentrations of nitrate and ammonium nitrogen.

Leachates produced from unlimed, sulphur-contaminated soils contained elevated levels of both nitrate and ammonium nitrogen. Nitrate values remained constant as soil sulphur levels increased, whereas ammonium levels tended to increase with increasing soil

TABLE 3.15. Electrical conductivity (mS cm^{-1}) of leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 3rd growth trial				
<0.1	1.42± 0.72[a]	1.16±0.34[a]	0.91±0.38[a]	1.20±0.35[a]
4	33.0 ± 5.12[c]	3.21±0.13[b]	3.41±0.14[b]	31.9±4.87[c]
9	74.0 ±18.0[d]	3.54±0.17[b]	3.79±0.20[b]	70.8±13.3[d]
14	141 ±21[e]	3.13±0.43[b]	4.41±0.19[b]	143±14[e]
b) Following 3rd growth trial				
<0.1	0.62± 0.32[a]	0.66±0.30[a]	0.49±0.35[a]	0.69± 0.35[a]
4	47.4 ± 7.64[c]	3.16±0.36[b]	3.34±0.16[b]	42.1± 3.8[c]
9	61.0 ±10.1[c]	3.47±0.22[b]	3.66±0.24[b]	57.6± 4.8[c]
14	108 ±22[d]	2.58[2]	3.86±0.36[b]	124 ±22[d]

[1]Data were analyzed by two-way ANOVA following log transformation. MSE for each trial was (1) 0.00438, and (2) 0.00398. Significant differences amongst log transformed means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < 0.05$).

[2] n = 1

TABLE 3.16. NO_3-N (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 3rd growth trial				
<0.1	30.3±14.3^{bc}	42.1±22.0^{c}	21.1±10.4^{bc}	15.1±7.0^{bc}
4	291±39^{d}	16.8±6.6^{bc}	19.3±5.8^{bc}	418±85^{d}
9	408±73^{d}	9.8±4.0^{b}	11.1±3.6^{bc}	398±95^{d}
14	660±74^{d}	1.5±2.0^{a}	7.7±1.9^{b}	618±87^{d}
b) Following 3rd growth trial				
<0.1	0.43±0.29^{2a}	11.4±3.7^{3,b}	ND	0.25±0.21^{3a}
4	473±84^{c}	0.53±0.06^{2a}	0.67±0.50^{a}	578±119^{c}
9	522±119^{c}	0.83±0.42^{a}	0.40±0.17^{a}	515±107^{c}
14	674±104^{c}	ND	1.3±1.7^{a}	706±151^{c}

[1]Data were analyzed by two-way ANOVA. MSE for each trial was (1) 0.02545, and (2) 0.01304. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < .05$).

[2] n=3
[3] n=2
ND = not determined

TABLE 3.17. NH_4-N (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 3rd growth trial				
<0.1	0.46±0.22^{ab}	0.50±0.13^{ab}	0.44±0.20^{a}	0.36±0.25^{a}
4	547±68^{c}	0.81±0.33^{ab}	1.3±0.4^{ab}	861±162^{cd}
9	1177±384^{d}	1.36±0.27^{ab}	1.9±0.3^{b}	1264±317^{d}
14	1841±238^{d}	1.1±0.6^{ab}	1.9±1.0^{b}	1668±241^{d}
b) Following 3rd growth trial				
<0.1	0.53±0.27^{a}	0.52±0.18^{a}	0.58±0.22[2]^{a}	0.41±0.21^{a}
4	925±110^{b}	0.35±0.09^{a}	0.39±0.34^{a}	1034±164^{bc}
9	1275±213^{bc}	0.48±0.09^{a}	0.44±0.16^{a}	1548±173^{bc}
14	1729±284^{c}	0.16[3]	0.74±0.54^{a}	2065±373^{c}

[1]Data were analyzed by two-way ANOVA. MSE for each trial was (1) 0.00696, and (2) 0.00489. Significant differences amongst means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < 0.05$).

[2] n=3
[3] n=1

sulphur concentration. Nitrate and ammonium concentrations within this group of leachates remained constant over time.

D. Phosphate concentrations in leachates

Phosphate-phosphorus concentrations in leachates from limed soils were not significantly different than those from control soils (Table 3.18). Similar to the ammonium and nitrate data, elevated phosphate levels were found in leachate from unlimed, sulphur-contaminated soils. There was no clear trend in phosphate concentration with increasing soil sulphur concentration.

Similar trends in phosphate values existed for both leaching episodes. No major changes in the magnitude of phosphate values occurred over time.

E. Sulphate in leachates

Trends in sulphate concentrations of leachates were similar for both two leaching trials (Table 3.19). Sulphate levels were highest in leachates produced from acid soils. Limed soils contained the next highest levels, while leachates from control soils had the lowest sulphate concentrations. These three groups were all statistically separate from each other.

Sulphate data collected from leachate trials did not pass the F_{max}-test. It was assumed that the ANOVA was robust enough to withstand the heterogeneity of variances inherent in these data sets.

F. Soluble aluminum, iron, and manganase in leachates

Unlike other leachate data, metal determinations were made only on selected samples taken following the third growth trial. The effect of manure was not investigated in terms of soluble metals in produced leachates. As only two replicate determinations were made, an ANOVA was not conducted.

From the mean values presented in Table 3.20, it can be noted that leachates from limed soils contained lower levels of soluble metals than leachates from control soils. No trend in these leachate metal concentrations was noted with changing soil sulphur levels.

Table 3.18. PO_4-P (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.[1]

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 3rd growth trial				
<0.1	0.17±0.12[a]	0.15±0.08[a]	0.59±0.20[a]	0.44±0.09[a]
4	53.0±16.2[b]	0.36±0.04[a]	0.57±0.10[a]	71.9±55.8[b]
9	169±40[c]	0.46±0.14[a]	0.66±0.09[a]	225±36[c]
14	116±25[bc]	0.48±0.12[a]	0.72±0.11[a]	183±47[c]
b) Following 3rd growth trial				
<0.1	0.17±0.16[a]	0.15±0.14[a]	0.37±0.18[2a]	0.35±0.22[a]
4	96.6[3]	0.12±0.02[a]	0.28±0.04[a]	123±22[2c]
9	161±24[cd]	0.16±0.02[a]	0.31±0.05[a]	232±37[d]
14	78.1±17.1[b]	0.33[3]	0.35±0.06[a]	147±34[c]

[1]Data were analyzed by two-way ANOVA following log transformation. MSE for each trial was (1) 0.01150 and (2) 0.00342. Significant differences amongst log transformed means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p < 0.05$).

[2] n=3
[3] n=1

Table 3.19. SO_4-S (mg L^{-1}) in leachate produced from pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Data are means (n=5) ± standard deviations.

Soil Sulphur (%)	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
a) Prior to 3rd growth trial				
<0.1	660±380[ab]	470±180[b]	430±310[a]	590± 260[2,ab]
4	38,120±10,790[c]	1560± 50[b]	1640± 80[b]	37,400±8090[c]
9	82,010±26,460[c]	1540± 40[b]	1600± 60[b]	81,700±12,640[c]
14	90,700±11,670[c]	1390±280[b]	1610±100[b]	55,760±23,780[c]
b) Following 3rd growth trial				
<0.1	330±200[2,a]	260±120[a]	460±350[3,a]	340±230[a]
4	50,870±26,190	2320±250[b]	2380± 90[b]	77,560±11,630[3,c]
9	85,460±5840[c]	2450±260[b]	2620±230[b]	82,540±22,890[c]
14	67,200±7850[c]	ND	3080±640[b]	63,860±16,210[c]

[1] Data in each trial were analyzed by two-way ANOVA, following log transformation. MSE for each trial was (1)0.02656, and (2)0.03909. Significant differences amongst log transformed means were detected by Scheffé multiple contrast test. Values in each trial followed by the same letter(s) are not significantly different ($p<0.05$).

[2] n = 4
[3] n = 3
[4] n = 2
ND = not determined

Table 3.20. Soluble aluminum, iron, and manganese (mg L^{-1}) in leachates produced from selected pot soil used for growth trials involving four sulphur levels upon which four reclamation treatments were superimposed. Leachates were produced following the third growth trial. Data are means (n=2) ± standard deviations.

Soil Sulphur (%)	Metal Measured	Reclamation Treatments: No Treatment	Lime	Lime and Manure	Manure
<0.1	Al	0.123±0.106	ND	ND	ND
	Fe	0.731±0.443			
	Mn	0.034±0.004			
4	Al	778±3	0.012±0.001	ND	ND
	Fe	4817±1439	0.124±0.039		
	Mn	514±34	0.008±0.008		
9	Al	1082±293	0.011±0.000	ND	ND
	Fe	8220±3224	0.119±0.045		
	Mn	419±169	0.005±0.006		
14	Al	526±163	0.008[1]	ND	ND
	Fe	2554±1055	0.016[1]		
	Mn	13.8±5.7	0.177[1]		

ND = not determined
[1]n = 1

Leachates from unlimed soils contained higher levels of soluble aluminum, iron, and manganese than did leachates from control soils. Highest leachate levels of metals were recorded from pots containing 9% sulphur. Further investigation would be required to determine if this trend is merely a function of low sample replication.

4.0 DISCUSSION

4.1 EFFECT OF SULPHUR CONTAMINATION ON PLANT GROWTH AND SOIL CHEMICAL PROPERTIES.

No plant growth occurred in any untreated soils containing sulphur. Initial germination occurred, but plants were unable to survive to trial completion. All of these soils had a pH of less than 4.5. This is below the pH that Webber et al. (1977) reported as the minimum pH (5.5) at which plant growth can successfully occur on agricultural soil. It is likely that the failure of plants to establish on these acidic soils was due to both direct and indirect effects of the low soil pH.

Within a soil that is heavily contaminated with elemental sulphur, microbial oxidation of sulphur to soluble sulphate will occur. A number of soil chemical properties are directly linked to the level of sulphur oxidation in soils. Both pH and conductivity corresponded closely to sulphate levels in acidified soils. When the rate of sulphur oxidation slowed, so did the resultant production of sulphuric acid. Hence, the observed pH values also leveled off.

Reduced rates of sulphur oxidation as a result of metal toxicity has been reported by Hart (1959). It is postulated that the leveling off of sulphate values (hence sulphur oxidation) in the acid soils was the result of metal toxicities in the soil limiting or inhibiting the survival of sulphur-oxidizing microorganisms. Levelling off of pH values occurred, however, at levels toxic to plant growth.

The same trend was observed for soil conductivity. The major ion contributing to the soluble salt concentration in these soils would be sulphate. Although sulphate-sulphur is not phytotoxic, it can accumulate to the point where the soil becomes saline (Leitch and Nyborg 1985). Conductivity values leveled off when sulphate values plateaued. Conductivity values in the sulphur-contaminated soils were, however, high enough to inhibit plant establishment. Reed canarygrass has been documented as growing in soils with conductivity values as high as 5 to 10 mS cm^{-1} (Watson et al. 1980). All of the acid, sulphur-contaminated soils in this study had conductivity values well above this range, with the exception of the data collected

prior to the first growth trial and the 4% sulphur soils following the first growth trial.

Sulphur oxidation in these soils was also indirectly related to other changes in soil chemical properties. Nitrate levels in all of the acid soils decreased relative to that in the control soils following the first growth trial. The decrease in nitrate levels corresponds well with the documented susceptibility of Nitrobacter to acid conditions (Rechcigl and Sparks 1985). There was, however, an apparent stimulation in nitrate production in the 4% sulphur soils as measured by samples taken following the second and third growth trials. Other researchers have also reported evidence of nitrification in acid soils. Uhlen (1985) observed that nitrification had occurred in a highly organic soil at a pH of 4.5, while Curtin and Smillie (1986) reported evidence of nitrification in a soil that had a pH of 4.2. Rechcigl and Sparks (1985) speculate that any nitrification that does take place below a pH of 4.5 may be the action of heterotrophic organisms. According to the results obtained in this study, nitrification was taking place in the soil down to a pH of approximately 1.9. Without further work to document why the nitrate was occurring in the 4% sulphur soils, the only speculation that can be made is that nitrification occurred in soils down to a pH of approximately 2.0.

In contrast, ammonium levels were higher in acid soils than in control soils. While this result has been reported in the literature (Rorison 1973; Rechcigl and Sparks 1985), the mechanisms of ammonium accumulation in acid soils are not well understood. While some report higher ammonium levels as a result of increased mineralization, it could be the result of impaired nitrification leading to an accumulation of ammonium. The data for both soluble forms of nitrogen indicate that normal cycling of nitrogen was impaired as a result of acidification.

Although a decrease in both phosphorus mineralization (Rechcigl and Sparks 1985) and the availability of soluble phosphorus (Leitch and Nyborg 1985) has been observed in acid soils, soluble phosphorus levels in sulphur-contaminated, acid soils in this study did not differ significantly from those in control soils. It

indicates that, in this study, either the microorganisms responsible for transformation of organic phosphorus to inorganic phosphate are capable of operating under extreme acidity or that a chemical process such as acid hydrolysis of organic matter is responsible for the levels of soluble phosphorus in the acid soils. It also indicates that available phosphorus is not being tied up as expected, due to the formation of aluminum and iron bound phosphates (Leitch and Nyborg 1985). Further investigations would be required to document this process and to identify whether it is biological or chemical in nature.

Sulphur contamination in soils taken from below a former sulphur block basepad caused a number of biological and chemical changes such as interrupted cycling of nitrogen, increased soil acidity, and increased soil concentration of soluble sulphate. These changes resulted in the soil being incapable of supporting plant growth.

4.2 EFFECTIVENESS OF LIME AND MANURE AMENDMENTS

Lime alone and in combination with manure was applied to sulphur-contaminated soils to test their effectiveness in encouraging plant growth and ameliorating soil conditions.

Based on the results of this study, lime amendation may not ensure reclamation of soils heavily contaminated with elemental sulphur. Lime applications were not effective in promoting plant growth at soil sulphur levels above 4%. These results are not in agreement with Nyborg (1982) and Bertrand (1973) who reported that soils contaminated with elemental sulphur could be successfully reclaimed despite the requirements for heavy lime applications. Bertrand applied 224 tonnes lime ha^{-1} to acidified soils of pH 1.4 and 2.1 and obtained successful crops of oats (Nyborg 1978). Nyborg (1982) reported that grasses grew well on soils that were limed with as much as 600 tonnes ha^{-1}. Liming rates for the sulphur-contaminated soils used in this experiment were as high as 893 tonnes ha^{-1}.

Both Nyborg and Bertrand studied sulphur-contaminated soils obtained from areas adjacent to sulphur handling facilities rather than soils located directly beneath a former sulphur block basepad (as was

the case in this investigation). Total sulphur values in Bertrand and Nyborg's soils were ≤1% and 10%, respectively. Comparable results from the present study do not concur that lime amendation of the contaminated soil will result in successful reclamation. Differences between the soils used in this project and those used in the two previous studies include the fact that soil taken from below the basepad would have been in contact with elemental sulphur for much longer than soils lying adjacent to sulphur handling facilities. In addition, the soil lying below the sulphur block basepad was subjected to very different microclimatic factors than was soil that did not support a block of sulphur for a minimum of twenty years.

Negative growth responses to high lime rates are well-documented (Haynes 1982). High rates of lime application are not unusual in agricultural soils which have been acidified through fertilizer use or climatic factors. Rates denoted as high for these soils (i.e., 25 tonnes ha^{-1}) are, however, at least ten-fold lower than lime additions incorporated into soils in this research.

Despite reports of organic matter reducing toxicities associated with acid soils (Hoyt and Turner 1975; Wright et al. 1985; Ahmad and Tan 1986), addition of manure to unlimed, sulphur-contaminated soils did not improve the growth of reed canarygrass. Therefore, the amount of manure that was added, 40 tonnes ha^{-1}, was not sufficient to reduce toxicities associated with acid soils. It would appear impractical to reclaim heavily contaminated soils with organic matter alone. Ahmad and Tan (1986) concluded that the addition of lime in combination with organic matter was more successful in reducing aluminum toxicity than the addition of organic matter alone. Under the conditions set forth in this study, addition of manure to limed soils did not significantly improve plant growth.

Lime additions to sulphur-contaminated soils resulted in changes to various soil chemical parameters. The pH of all soils amended with lime increased to neutrality and remained neutral for the duration of the experiment. Neutralization of these soils raised the pH to a level where plant growth would not be impeded by direct or indirect effects of acidity.

Another important chemical parameter that could influence reclamation success is soil salinity as measured by conductivity. Bertrand (1973) found that the use of calcium carbonate containing greater than 5% magnesium carbonate resulted in levels of soluble salts which could hinder plant growth. The lime used for this experiment did not contain more than 5% magnesium carbonate (G. Crosby, pers. comm.). The conductivity values of all limed soils were below 4.0 mS cm^{-1}; conductivities above this value are generally considered indicative of saline soils (Hausenbuiller 1978). The reduction in growth, therefore, was not due to elevated levels of soluble salts in the limed soils.

The general fertility status of the sulphur-contaminated soils was also altered as a result of liming. Liming resulted in an initial increase in nitrate-nitrogen values compared with control soils. Nitrate values in all soils decreased during the course of the experiment, despite fertilization at the beginning of each trial. Although nitrate values were quite low, especially after the leaching trials, levels in the limed soils did not fall below those in control soils. Given that reed canarygrass growth in the control soils was always lush, it does not appear that plant growth in limed soils was limited by a lack of nitrate-nitrogen. Given the similarity of ammonium values in the limed soils compared to those in the control soils, levels of this plant nutrient did not cause the growth depression observed in the limed soils.

The major plant nutrient affected by liming was phosphate. In soil samples taken throughout the experiment, phosphate values in limed soils were significantly lower than those in control and acid soils. Various publications (Sims and Ellis 1983; Pombo and Smith 1986) report deficiencies or elevations in the status of available phosphorus as a result of lime applications. Results from this experiment clearly indicate a reduction in phosphorus in limed, sulphur-contaminated soils.

There are different ways to determine the lime requirement of a soil. There are two different types of acidity within a soil; active acidity and reserve acidity (Brady 1984). Active acidity requires immediate neutralization. In a soil that is heavily

contaminated with elemental sulphur, a proportion of the soil acidity will be reserve acidity due to the presence of unoxidized elemental sulphur. In this experiment, lime was added on a chemical basis to ensure that all of the generated acidity would be neutralized. Lime requirements based on the amount of lime required to neutralize the active acidity are a minimum of ten-fold lower than the amount of lime actually applied to the pots in this experiment.

Overliming can result in phosphorus deficiencies (Brady 1984). The decreases in available phosphorus in limed soils are likely due to precipitation of insoluble compounds containing phosphate and calcium. Reductions in aboveground biomass in the limed soils may have been due to a phosphate deficiency. Plants suffering from a lack of phosphate develop red stripes along their leaves (Agrios 1969) but no such symptoms were noted. Plants germinated in the limed pots, but would begin to dieback about two weeks later. The symptoms suggested that the plants were desiccating due to a possible lack of moisture but all pots were watered to two-thirds of their field capacity, so moisture should not have been a limiting factor.

The addition of manure alone or in combination with lime did not affect many soil chemical parameters. Phosphorous values were higher in all soils that were treated with manure. Available nitrate-nitrogen measured prior to the growth trials was higher in manure-treated soils but no significant differences were detected in subsequent soil sampling periods. Although the addition of manure did initially improve some soil fertility levels, such as available phosphate and nitrate, no improved yields of reed canarygrass resulted. It had been expected that the manure would be effective in neutralizing soil acidity in the sulphur-contaminated soils, to some extent, and would also provide additional nutrients through the ongoing breakdown of organic material, but this did not appear to be the case.

In summary, lime amendation of a soil taken below the basepad of a former sulphur block did reclaim the soil by improving soil chemical characteristics and plant growth. Reclamation success was not complete, however, in that aboveground biomass of reed canarygrass was reduced compared with control pots. It is postulated that the

reduced yields measured on limed soils compared to those on control soils was due mainly to the physical presence of the lime itself. Although changes in soil texture were not measured, visual changes to the soil structure were noted. As the amount of lime was increased, the soil was much harder to break apart and cultivate. Overliming can reduce both phosphorus availability and pore space (Brady 1984). The consequences of less pore space are reduced water and air necessary for healthy root growth. Although root biomass was not measured quantitatively, roots growing in limed soils were observed to be less developed than those in control soils. The observation that plants appeared to be dying of desiccation also supports the hypothesis of overliming.

The design of this experiment does not permit differentiation between the effects of lime itself compared with the effects of the combination of lime and sulphur in the soil on plant yield and soil chemistry. Reduced plant yields and altered soil chemistry could conceivably be due to two possible factors: (1) the physical presence of lime alone, or (2) a combination effect of the presence of both lime and sulphur in the soil.

There is a possibility that the sulphur-contaminated soils could be successfully reclaimed with a change in liming practices. As has already been discussed, neutralization of the active soil acidity required only a fraction of the actual amount of lime applied. Reduced initial applications of lime followed by additional applications as required, should minimize the possibility of overliming the soil. Further work is required to determine what levels of lime should be initially applied to soils containing high levels of elemental sulphur. Adequate liming is necessary to ensure neutralization of acidity produced as a result of any continued sulphur oxidation.

The addition of manure as an amendment is also recommended, despite the poor results achieved in this experiment. Consideration should be given to adding more manure throughout the reclamation process to progressively improve soil conditions. Nutrient additions, as required, should be added in the form of fertilizers.

4.3 CHEMICAL CHARACTERISTICS OF LEACHATES

The objective of the leaching trials was to chemically characterize the leachate produced from the various soil mixtures. No attempt was made to relate plant nutrient concentrations in leachates with those measured in the soils.

Acidic leachates were produced from all unlimed, sulphur-contaminated pots, while leachates from limed pots were neutral. Leachate acidity increased with increasing sulphur level. Soluble aluminum, iron, and manganese concentrations in leachates produced from limed soils were well below 1mg L^{-1}, while concentrations in the unlimed, acidic leachates were recorded in the hundreds of mg L^{-1}. These results indicate the potential for groundwater metal contamination from sulphur-contaminated soils that are not limed immediately following basepad removal. Sulphate concentrations occurred in acidic leachates in levels as high as 0.9% while concentrations in leachates from limed soils were measured in the mg L^{-1} level. High levels of other nutrients, such as nitrogen and phosphorus, were also present in acidic leachates. In contrast, nutrients leached from limed soils were not significantly higher than those from control soils.

Leaving a soil that is heavily contaminated with elemental sulphur exposed and unlimed is not only a hazard as a result of the metal concentrations that could potentially reach the groundwater, but also a drain of potentially available nutrients that are required for reclamation. Conductivity values were greater in leachates from unlimed soils than those from control or limed soils. The increase in soluble salts present in acidic leachates was due to the presence of high levels of sulphate.

The results obtained in this study suggest that leachates from limed, sulphur-contaminated soils would not present a hazard to local groundwater supplies but acidic leachates from unlimed, sulphur-contaminated soils may contaminate groundwater. Chemical characterization of leachates from acidic soils illustrate the importance of quickly neutralizing contaminated soils.

5.0 CONCLUSIONS

The following conclusions were drawn from results of the experiments conducted:

1. Plant growth did not occur in any untreated sulphur-contaminated soils;
2. Lime applications, at a rate of 3 parts lime:1 part total sulphur, were not effective in promoting plant growth at soil sulphur levels above 4%;
3. Reclamation of sulphur-contaminated soils by manure additions, alone, was not successful;
4. Nitrogen cycling, as determined by nitrate and ammonium measurements, was disrupted in unlimed, sulphur-contaminated soils;
5. Lime applications to sulphur-contaminated soils maintained soil pH values at neutrality.
6. Amounts of lime added to contaminated soil were a minimum of 10-fold higher than that required to neutralize the active acidity within the soil.
7. Reclamation failure of limed soils is postulated to be due to the physical presence of lime. A second possibility not tested in this experiment is that reclamation failure could also be due to a combined effect of both the lime and sulphur in the soil.
8. Acidic leachates were produced from all unlimed, sulphur-contaminated soils, while leachates from limed soils were neutral. Leachate acidity increased with increasing sulphur level.
9. Soils that have underlain a sulphur block basepad should not be left exposed and unlimed. Immediate liming to prevent potential migration of acidic leachate into the groundwater is recommended.

6.0 LITERATURE CITED

Agrios, G.N. 1969. Plant Pathology. Academic Press, New York.

Ahmad, F. and K.H. Tan. 1986. Effect of lime and organic matter on soybean seedlings grown in aluminum-toxic soil. Soil Soc. Am. J. 50(3): 656-660.

Bertrand, R.A. 1973. Reclaiming of Soils Made Barren by Sulfur From Sour Gas Processing Plants. M.Sc. Thesis, University of Alberta.

Black, C.A. 1965. Methods of soil analysis. Part 1 - Physical and mineralogical properties, including statistics of measurement and sampling. Agronomy No. 9. American Society of Agronomy, Inc., Madison, Wisconsin.

Brady, N.C. 1984. The Nature and Properties of Soils. 9th Edition. Macmillan Publishing Company, New York.

Brower, J.E. and J.H. Zar. 1977. Field and laboratory methods for general ecology. Wm. C. Brown Co., Cubuque, Iowa.

Curtin, D. and G.W. Smillie. 1986. Effects of liming on soil chemical characteristics and grass growth in laboratory and long-term field-amended soils. Plant Soil 95: 23-31.

Hart, M.G.R. 1959. Sulfur oxidation in tidal mangrove soils of Sierra Leone. Plant Soil 11: 215-236.

Hausenbuiller, R.L. 1978. Soil Science: Principles and Practices. Wm. C. Brown Co., Dubuque, Iowa.

Haynes, R.J. 1982. Effects of liming on phosphate availability in acid soils. Plant Soil 68: 289-308.

Hoyt, P.B. and R.C. Turner. 1975. Effects of organic materials added to very acid soils on pH, aluminum, exchangeable ammonium and crop yields. Soil Sci. 119: 227-237.

Hyne, J.B. 1986. Managing solid sulphur wastes. Presented at the Petroleum Waste Management Conference, 22-23 January 1986, Calgary, Alberta.

Leitch, R.H. and M. Nyborg. 1985. Reclamation of sulphur contaminated soils. In: Proc. Sulphur '84 Conf. Sponsored by SUDIC, June 3-6, 1984. Calgary, Alberta.

McKeague, J.A. (ed.) 1978. Manual on Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. Ottawa, Canada.

Nyborg, M. 1978. Sulfur pollution and soils. In: J.O. Nriagu (ed.), Sulfur in the Environment: Part II. Ecological Impacts. J. Wiley and Sons, Inc.

Nyborg, M. 1982. Effects of sulphur deposition on soil. In: Agriculture and the Environment. Proc. of the Canadian Society of Environmental Biologists Symposium, March 6, 1982. Red Deer, Alberta.

Page, A.L., R.H. Miller, and D.R. Keeney. 1982. Methods of soil analysis. Part 2 - Chemical and microbiological properties. Agronomy No. 9, Part 2, 2nd edition. Soil Science Society of America, Inc., Madison, Wisconsin.

Peters, T.W. and W.E. Bowser. 1960. Soil survey of Rocky Mountain House Sheet. University of Alberta. Alberta Soil Survey Report No. 19. Edmonton, Alberta.

Pombo, G.I. and C.B. Smith. 1986. Growth and nutrient inter-relationships of three vegetable crops with different sensitivites to soil pH as affected by lime and fertilizer treatments. Commun. in Soil Sci. Plant Anal. 17(3): 353-368.

Rechcigl, J.E. and D.L. Sparks. 1985. Effect of acid rain on the soil environment: a review. Commun. in Soil Sci. Plant Anal. 16(7): 653-680.

Rorison, I.H. 1973. The effect of extreme soil acidity on the nutrient uptake and physiology of plants. In: H. Dost (ed.), Acid Sulphate Soils. Proc. Int. Symp. on Acid Sulphate Soils held August 13-20, 1972. Wageningen, The Netherlands.

Sims, J.T. and B.G. Ellis. 1983. Adsorption and availability of phosphorus following the application of limestone to an acid, aluminous soil. Soil Sci. Soc. Am. J. 47: 888-893.

Technicon. 1976. Ortho phosphate in water and wastewater. Industrial Method No. 94-70 W/B. Technicon Instruments Corporation, Terrytown, New York.

Technicon. 1977. Ammonia in water and wastewater. Industrial Method No. 98-70 W/A. Technicon Instruments Corporation, Terrytown, New York.

Technicon. 1978. Nitrate and nitrite in water and wastewater. Industrial Method No. 100-70 W/B. Technicon Instruments Corporation, Terrytown, New York.

Technicon. 1978a. Sulfate in water and wastewater. Industrial Method No. 118-71 W/B. Technicon Instruments Corporation, Terrytown, New York.

Uhlen, G. 1985. The toxic effect of aluminum on barley plants in relation to ionic composition of the nutrient solution. I. Water culture experiments. Acta Gric. Scand. 35: 265-270.

Watson, L.E., R.W. Parker, and D.F. Polster. 1980. Manual of Species Suitability for Reclamation in Alberta. Alberta Land Conservation and Reclamation Council Report #RRTAC 80-5.

Webber, M.D., P.B. Hoyt, M. Nyborg, and C. Corneau. 1977. A comparison of lime requirement methods for acid Canadian soils. Can. J. Soil Sci. 57: 361-370.

Wright, R.J., J.L. Hern, V.C. Baligar, and O.L. Bennett. 1985. The effect of surface applied soil amendments on barley root growth in an acid subsoil. Commun. in Soil Sci. Plant Anal. 16(2): 179-192.

Zar, J.H. 1984. Biostatistical Analysis. 2nd Edition. Prentice Hall, Inc., N.J.